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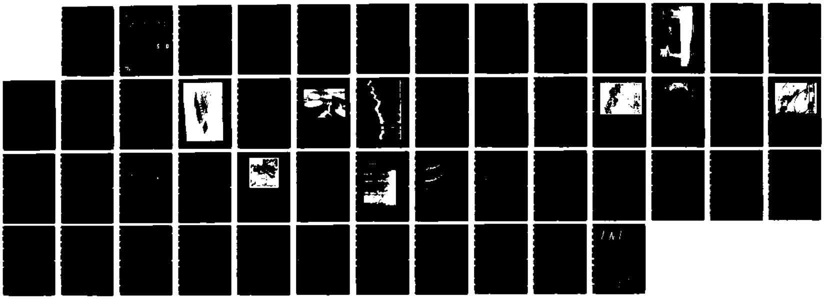

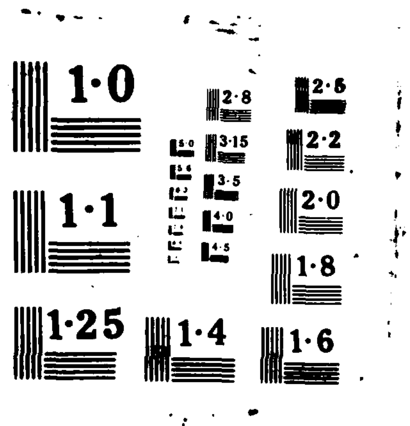
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REMOTE SENSING OF THE ATMOSPHERE IN THE VICINITY OF THE BATTLE GROUP

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Dr. Louis A. Hembree, Jr.
Naval Environmental Prediction Research Facility

AUGUST 1986

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This report discusses classes of instruments that can be used to remotely monitor the atmosphere in the vicinity of the battle group. The parameters measured by the instruments are given; the advantages and disadvantages of each instrument are cited. It is concluded that doppler radar and lidar used in combination provide the best overall measurement capability for the parameters of interest under the broadest range of operating conditions. It is recommended that lidar systems development be continued and that meteorological radar applications be adapted or developed for shipboard use. For measurement of temperature and humidity profiles under EMCON, the multispectral radiometer may prove to be useful with further development. It is also recommended that an examination be made to determine the time and space scales needed for remotely sensed data as they apply to the tactical needs of the battle group, with a follow-on trade-off analysis to recommend instrument development for the Navy.

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CONTENTS

1. INTRODUCTION

Atmospheric conditions have always had an impact on the Navy's operations. The state of the atmosphere determines whether or not an aircraft can take off or land, the route ships should travel, the radar propagation patterns, and many other operational factors that affect tactical decisions. Atmospheric parameters are currently measured in a more or less gross manner. For example, the presence of rain throughout a general area might be apparent without possessing knowledge of the rainfall intensity. Likewise, winds can be measured aboard ship, but it is much more difficult to characterize the wind some miles away. Yet, in either case, the latter information may be most important. Precise knowledge of electromagnetic and electro-optic propagation conditions is extremely important, yet the vertical profiles used to estimate ducting patterns and propagation conditions are obtained using radiosondes with limited resolution at too infrequent intervals.

The increased cost of weapon systems requires that the effects of the atmosphere on their operation be taken into account more fully than in the past. Also as weapons systems become more sophisticated, the edge could easily go to whoever can best monitor the atmosphere in the vicinity of their ships. The modern navy needs to be able to measure atmospheric parameters much more accurately and more frequently than before.

Atmospheric properties of prime concern: refractivity, visibility temperature, humidity, turbulence, and winds. Also of concern are precipitation patterns, wind fields near ships, and wind gusts and shears. A vertical profile of refractivity would allow the direct determination of ducting characteristics. If the refractivity profile cannot be determined directly then profiles of temperature and moisture are required to calculate the refractivity for ducting calculations. Evaporation ducting is of great concern, therefore a method of obtaining the profiles in the lower 50 to 60 meters of the atmosphere would be useful. The

ability to measure the wind field around a carrier would allow an improved determination of the optimum heading for aircraft launch and recovery. It would allow the early detection of gust fronts and wind shift lines that could adversely affect aircraft operations. The precipitation and wind fields could also be used for missile launch planning.

Recent technology advancements are making possible better assimilation of environmental data and models to support the missions of the battle group. Programs such as the Shipboard Meteorological and Oceanographic Observing System (SMOOS) and the Tactical Environmental Support System (TESS) are beginning to bring these newer technologies to the fleet. The objective of this report is to present and discuss surface based instrument systems that might be used to remotely monitor the lower atmosphere in the region around the battle group. The detailed theory and operation of each system will not be discussed, but a general overview will be given. Strengths and weaknesses of the various systems will be presented. The instrument systems to be addressed are presented in Table 1. Except for the radiosonde, all the systems are remote sensing systems. Other in situ instruments will not be addressed. In situ sampling of surface parameters has been addressed in SMOOS (Penny et al., 1983).

Table 1. List of instruments to be addressed.

Radiosonde
Microwave Radiometer
Acoustic Sounder
Doppler Acoustic Sounder
UHF/VHF Profilers
Radar
Doppler Radar
Lidar
Doppler Lidar

2. INSTRUMENTS

2.1 Scope

In this section each of the instrument systems listed in Table 1 will be discussed. The discussion will include the parameters measured, the quality of the measurements, and the advantages and disadvantages of each system.

2.2 Radiosonde

The radiosonde or rawinsonde has been around a long time. In its older basic configuration it measures temperature and humidity at preset pressure levels. Also the mean winds within a layer can be determined; however, winds are not currently obtained from shipboard radiosonde releases.

For standard radiosondes the current accuracy of the measurements is typically ± 0.2 to 2.0°F for temperature, ± 5 to 10% for humidity and ± 2 to 4 mb for pressure. A review of radiosonde humidity and temperature errors by Pratt (1985) revealed that large errors could occur with the humidity sensor due to thermal lag and its tendency to exhibit hysteresis. The radiosonde profile is often the profile to which other profiling systems are compared even though multiple sondes often do not compare well with each other.

Data acquisition takes between 1 to 2 hours for a typical sounding. The time needed to reduce the data depends on the method being used. Hand reduction of the data can take another hour or more. However, modern systems which automatically process data as it is received can produce a completed profile almost immediately upon receipt of the data.

As mentioned above most radiosondes acquire data at preset pressure levels. A pressure switch is used to switch between the humidity and temperature sensors as the balloon rises. The pressure interval corresponds to about 95 m at the surface and increases with altitude. This gives sufficient vertical resolution for profiling the lower atmosphere in most cases. When the

boundary layer is of interest, however, often a finer vertical resolution is desired. The finer resolution is needed for the determination of ducting characteristics. In newer model radiosondes the sampling takes place at a fixed time interval and the vertical resolution can be made as small as desired. If the sampling interval is too small the instrument lags become a problem. Special signal processing can account for the sensor time lag to some degree.

The minisonde is a radiosonde system developed for the Navy to take advantage of newer technology. It will have a higher vertical resolution than current Navy radiosondes, will have the additional capability to obtain winds, and will perform automatic data reduction. It is designed to interface with SMOOS and hence with TESS.

Two special sondes are being investigated by the Navy for use under EMCON. The first of these is one that stores the measurements on board the sonde, then transmits the entire sounding in a burst transmission. The burst transmission minimizes the chance of detection by hostile forces. The initial version would not include a wind measurement capability. The other approach that has been looked at is the use of a fiber optic cable. The cable would be trailed behind the sonde connecting it to the ship. Measurements would then be sent along the cable to the ship.

One of the biggest problems with radiosondes is the frequency of launches. In order to monitor the evolution of ducting, observations need to be taken much more often than twice a day because the boundary layer can change significantly over a short period of time. The normal frequency is two per day and it may not be feasible to increase the frequency of the launches for two reasons. One, onboard ship the frequency of launches may be lower due to flight operations or other circumstances that preclude them. Often when the observations are most needed, they cannot be taken. Another reason is that radiosondes use a lot of expendables, e.g., gas, balloons, and sondes. If the frequency

of launch is increased, more of these supplies would have to be stored onboard ship where space is already at a premium. The development of the mini-sonde will reduce the amount of gas required and the space required, but the space needed would still be substantial.

2.3 Microwave Radiometer (surface based)

A microwave radiometer is a passive device relying on the naturally emitted microwave radiation in a particular frequency band or bands. In its simplest configuration it measures the total liquid water along its beam. In a more complex configuration it can measure the liquid water content and temperature in range increments to a maximum range between 2 and 3 km. The resolution is best at near ranges and deteriorates as range increases. Some radiometers can be scanned in both azimuth and elevation to provide moderate spatial and temporal resolution data. A typical scan time for a single 360 degree scan at a given elevation angle is about 5 minutes. The accuracy is reasonable. An advantage of the microwave radiometer is that it is a passive device and therefore can operate during EMCON.

Using multispectral microwave radiometers (Figure 1), vertical profiles of temperature and humidity can also be obtained using inversion techniques similar to those using satellite radiometric data (Westwater et al., 1985; Decker et al., 1978; Wang et al., 1983). Figure 2 is an example of the profile obtained for a simple case. Accuracy is good for levels below 500mb when compared to radiosondes and better than that obtained from satellite for the same region. Figure 3 shows the profile measured during a ground based inversion. The reproduction of the profile is still fairly good.

Upper level inversions are not reproduced as well and could be missed entirely (see Figure 4). The higher the altitude of the inversion, the more difficult it is for the radiometer to detect it. This could be a major problem if the retrieved profiles were to be used for the calculation of elevated ducts. If the vertical resolution could be improved, the microwave radiometer could prove

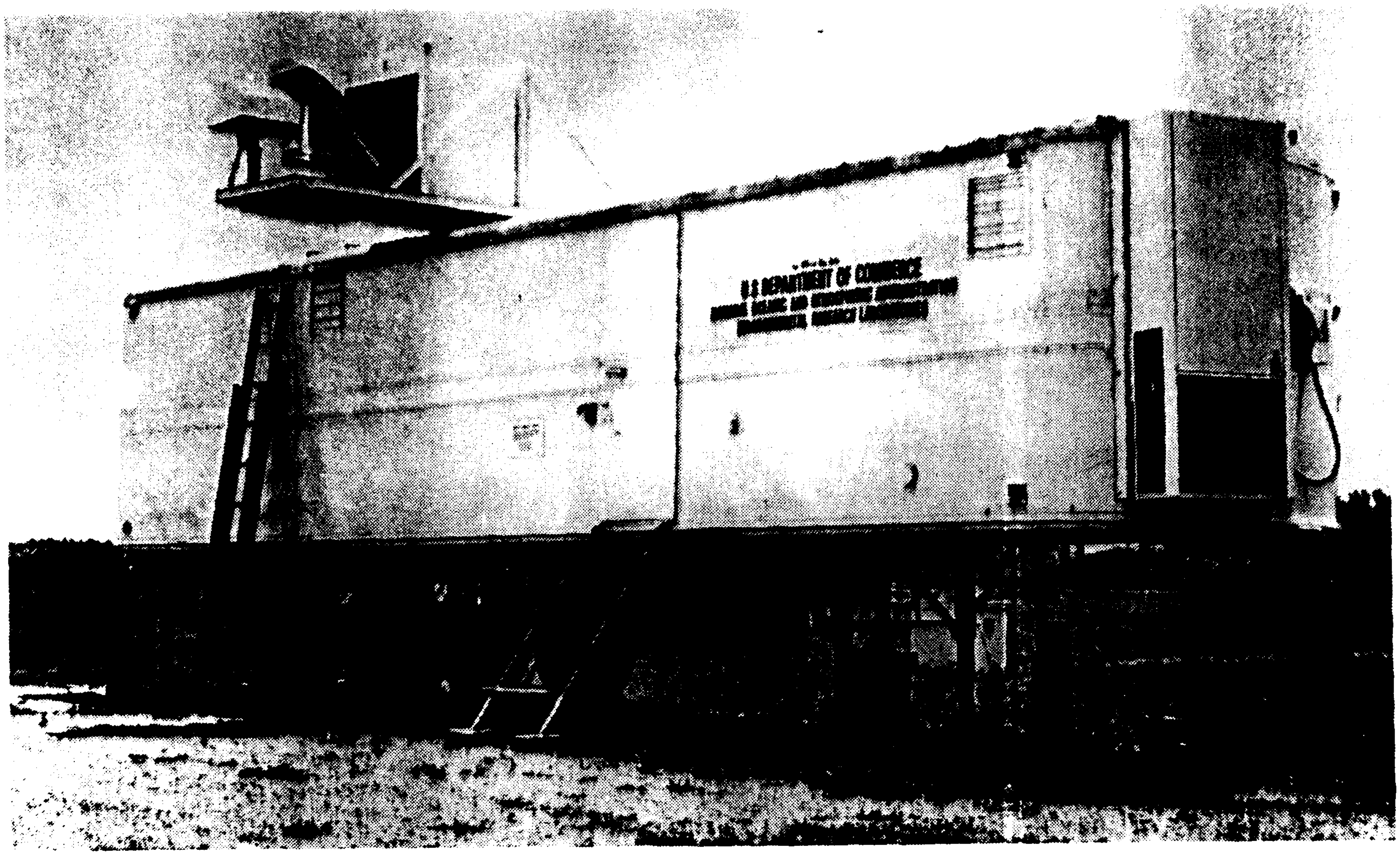


Figure 1. External view of the scanning antenna for the NOAA prototype 3 channel water vapor radiometer. Probable external dimension for a field unit for naval applications should be less than 1x1x2 m.

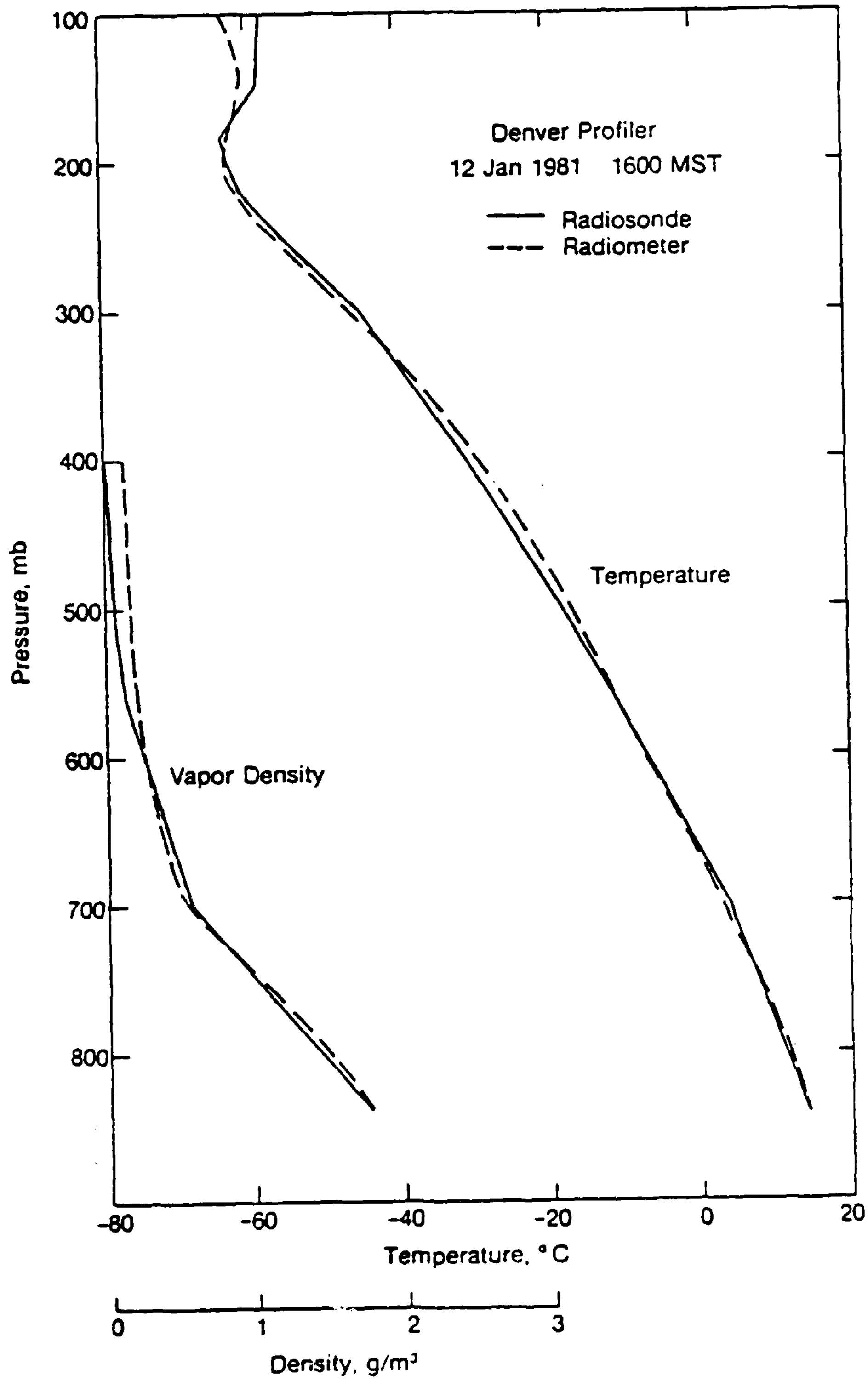


Figure 2. Comparison of simultaneous, colocated radiometric and radiosonde observations of simple temperature and humidity profiles. Figure courtesy of Mr. Martin Decker of NOAA/ERL.

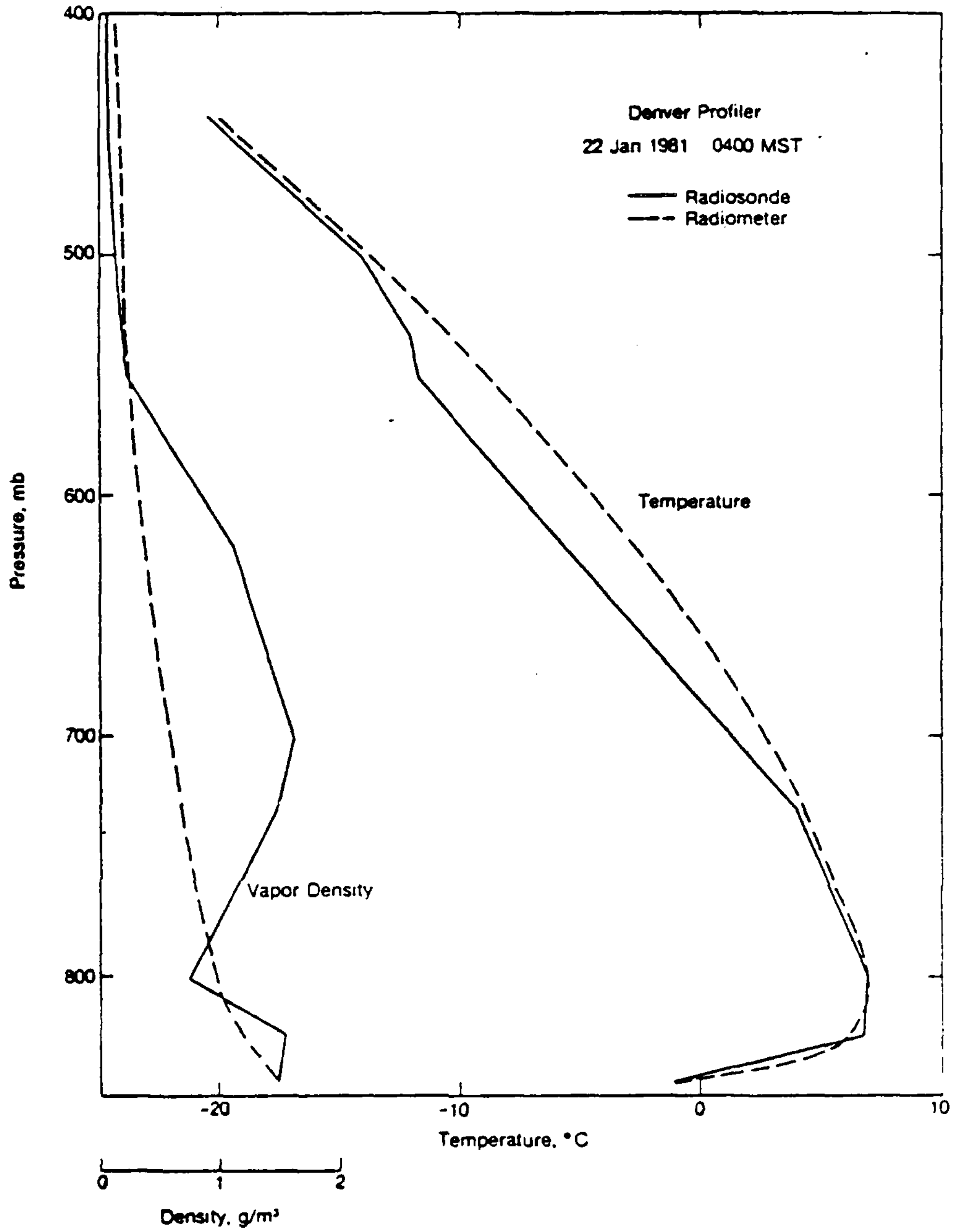


Figure 3. Comparison of colocated radiometric and radiosonde observations of temperature and humidity profile with a surface based inversion present. Note the reasonably good fit for the temperature, but the poor fit for water vapor. Figure courtesy of Mr. Martin Decker of NOAA/ERL.

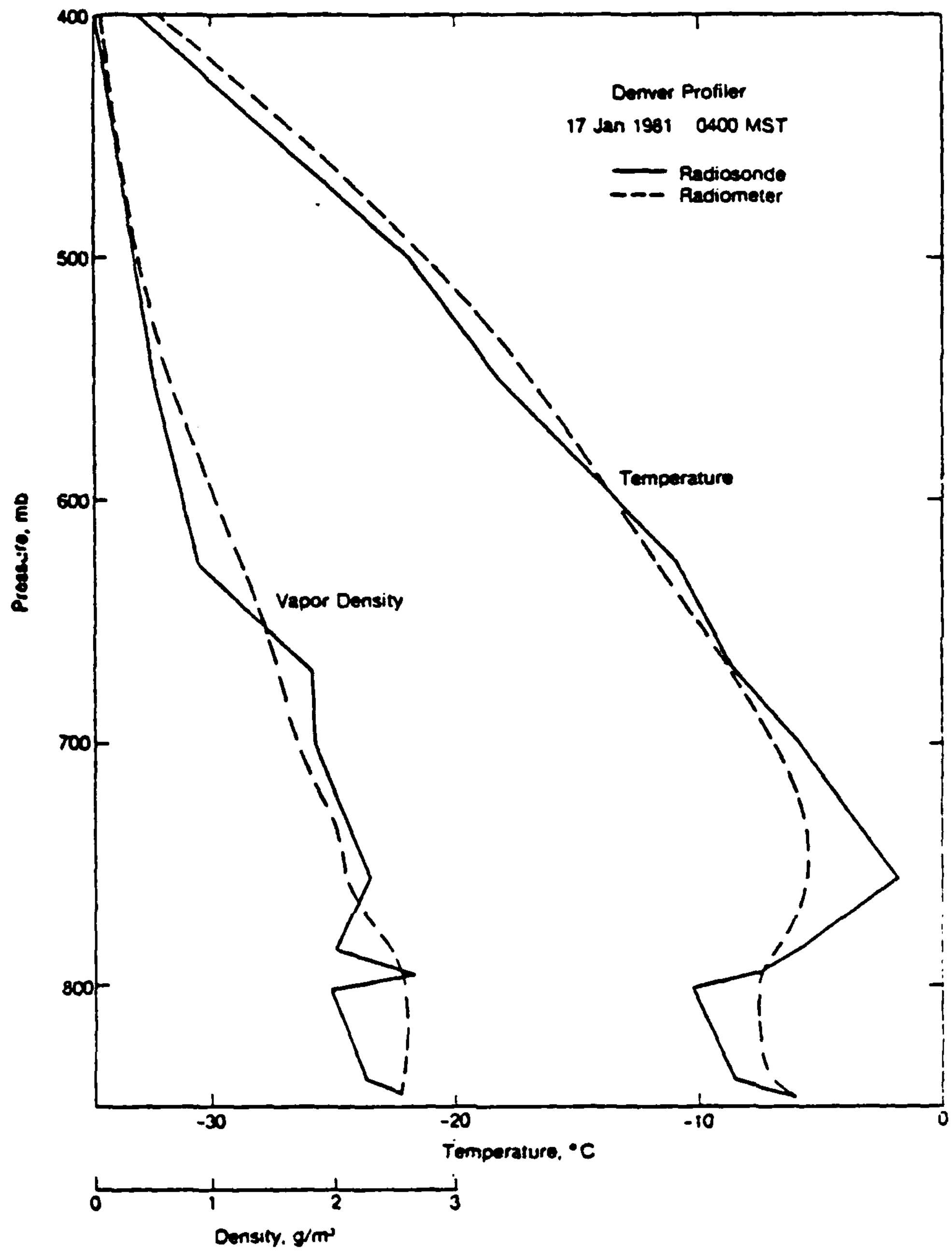


Figure 4. Comparison of simultaneous, colocated radiometric and radiosonde observations of temperature and humidity profiles with an elevated inversion. Note the large amount of smoothing that occurs. Figure courtesy of Mr. Martin Decker of NOAA/ERL.

to be a useful tool. One means of improving the resolution is by the inclusion of temperature inversion height information as additional constraints in the mathematical inversion process. The temperature inversion information could be obtained from other sensors such as a UHF/VHF profiler or lidar.

2.4 UHF/VHF Profilers

UHF/VHF profilers are used to profile the mean winds in the atmosphere, mainly above the boundary layer (Zamora and Shapiro, 1984; Larsen and Röttegr, 1982; Balsley and Gage, 1982). Figure 5 is an example of a wind profile time history. Sampling rates as high as 2 to 4 minutes per profile are obtainable, however longer averaging times are usually used. Research also indicates that the height of elevated inversions and the tropopause may be measured (Westwater et al., 1983, 1985).

The frequencies usually used are in the 40 MHz to 900 MHz range. The longer wavelength limit is controlled by antenna size and radio interference problems. As the frequency decreases the antenna size increases. At 40 MHz the antenna is typically a phased array between 50m and 100m on a side, which is about the practical limit. Figure 6 is an example of the phased array antenna for a 400 MHz system.

The short wavelength limit is controlled by the scattering mechanism. For the clear air environment in which profilers operate the scattering mechanism is the spectrum of refractive turbulence at scales of L/2 (L = wavelength). If the L/2 scale is within the inertial subrange of turbulence, then echoes can be detected. However, if the L/2 scale is within the viscous dissipation range, the turbulence is rapidly damped and the radar reflectivity decreases. Experience has shown that at 900 Mhz (33 cm), radar experiences cutoff for heights above 8-12 km (Chadwich et al.,1984).

Another determining factor is the sensitivity to hydrometeors. At 50 MHz precipitation has no significant effect. However, as the frequency increases, precipitation poses a greater problem. This is because the strength of the return

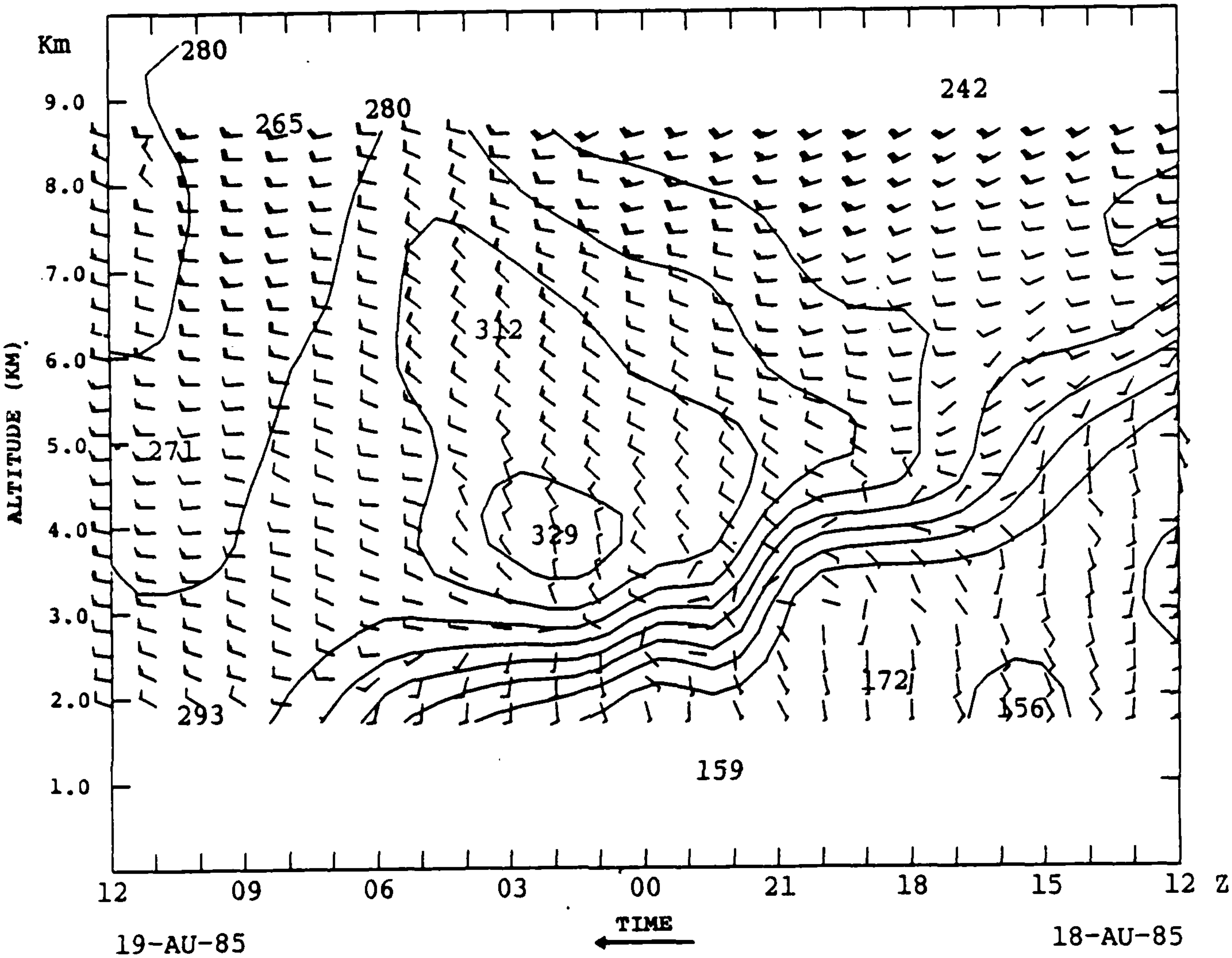


Figure 5. Time-height sector of hourly average profiler winds recorded using the Pennsylvania State University Shanty Town 59 MHz radar. Time period is from 12 GMT 18 August (right) to 12 GMT 19 August (left) 1985. Major ordinate divisions are km; msl. Radar site altitude is approximately 400m. Isopleths are of wind direction in 20° increments and vertical resolution is set at 300m. The section shows a cold front passage associated with the remnants of Hurricane DANNY as the system passed over Pennsylvania.

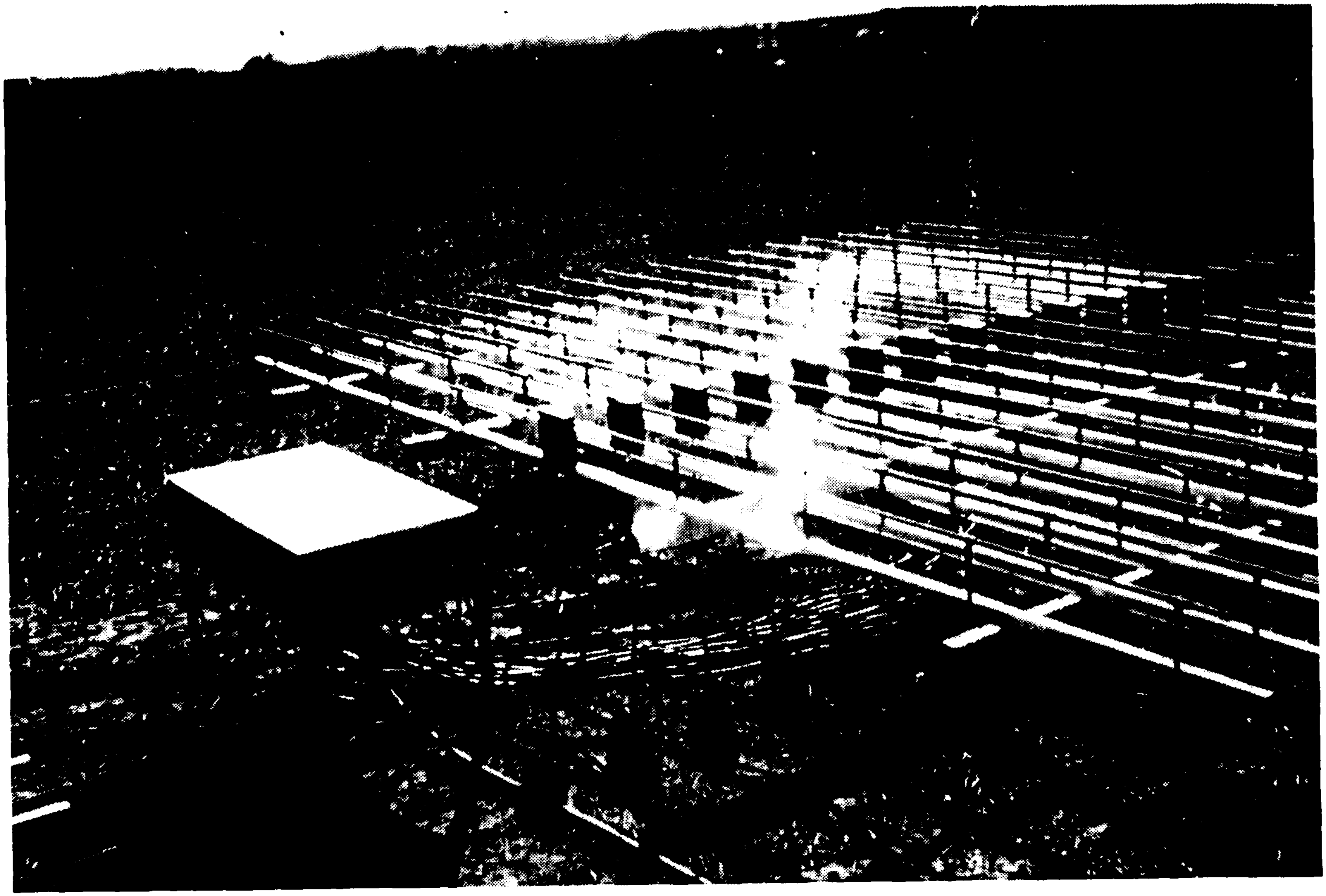


Figure 6. One set of elements of an orthogonal pair in a 400 MHz co-co (colinear-coaxial) profile antenna. Approximate dimensions are 6.1x7.6m, beamwidth is 4°. Photo courtesy of Dr. D. Thomson of Pennsylvania State University.

from the precipitation increases and the vertical velocity of the precipitation masks the velocity measurements from the turbulence. At frequencies of 400 Mhz and above, precipitation can significantly affect the measurements. If the precipitation is strong enough the wind profile cannot be recovered, and the system will be inoperative some percentage of the time due to precipitation. The percentage will increase as the frequency increases.

The size of the antenna required could place severe limitations on shipboard use. Even at 400 MHz the antenna would be an array between 7 and 12 meters on a side. At 900 MHz the antenna would be between 3 and 6 meters, but then the system would be limited in maximum altitude and be severely affected by precipitation.

2.5 Acoustic Sounder

Acoustic sounders are used to measure inversion heights and the thermal structure of the boundary layer. Figure 7 shows an acoustic sounder used by the Naval Postgraduate School for research, and Figure 8 is an example of the output. The development of acoustic sounders or sodars over the past decade or so can be traced to Little's (1969) analysis of the potentials of the technique. Ottersten and Hågård (1980) give a good overview of sodar principles.

An acoustic sounder consists of an antenna system through which sound pulses are emitted and the reflected signal received. The antenna system can use a single antenna for both transmitting and receiving (monostatic system) or it can use two antennas, one for transmitting and one for receiving (bistatic system) (see Figure 9). Both types are used. The frequency used is usually between 1000 and 5000 Hz. The choice of frequency affects the maximum range to which measurements can be made. The higher the frequency the shorter the maximum range. The acoustic waves are scattered due to the variability in air density and wind velocity.

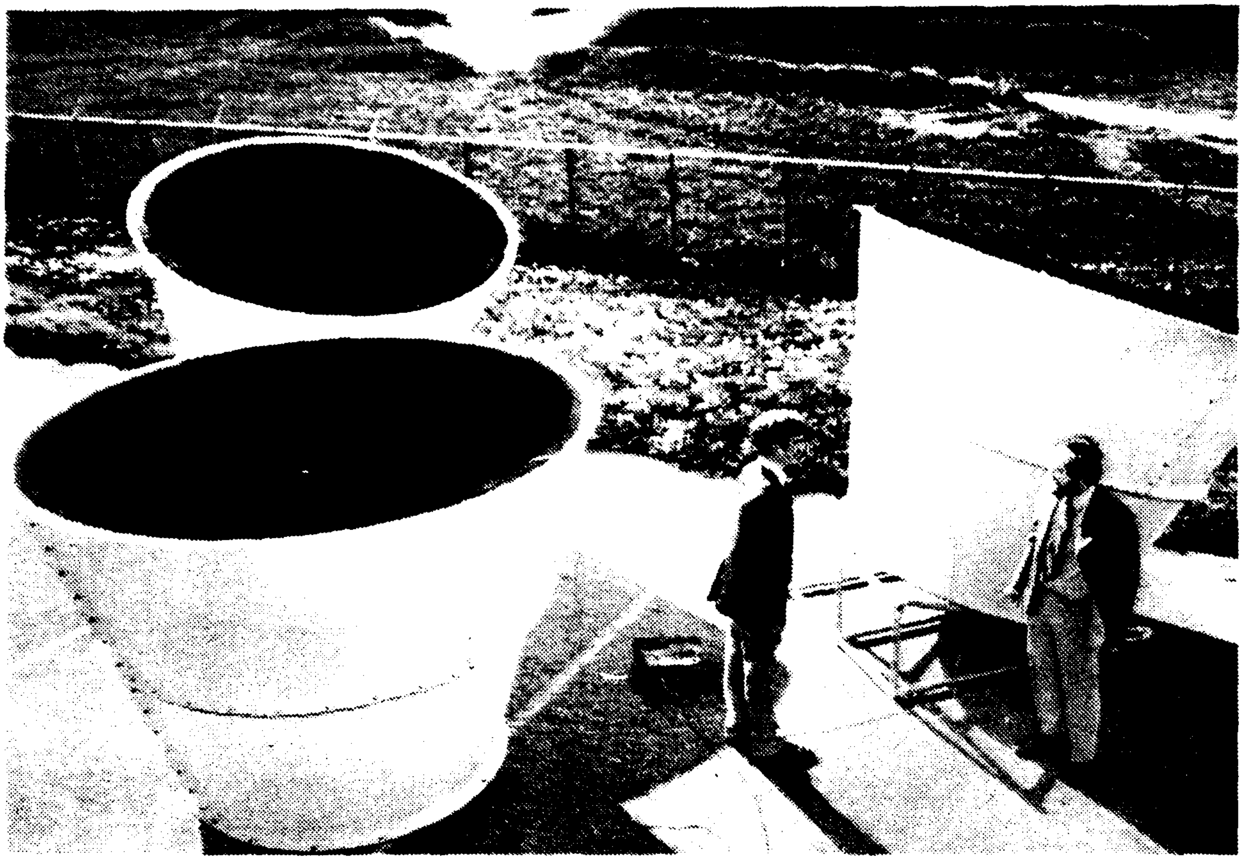


Figure 7. Three axis doppler acoustic sounder. A non-doppler sodar consists of only the vertically pointing antenna. *Photo courtesy of Dr. W. Shaw of the Naval* Postgraduate School, Monterey, California.

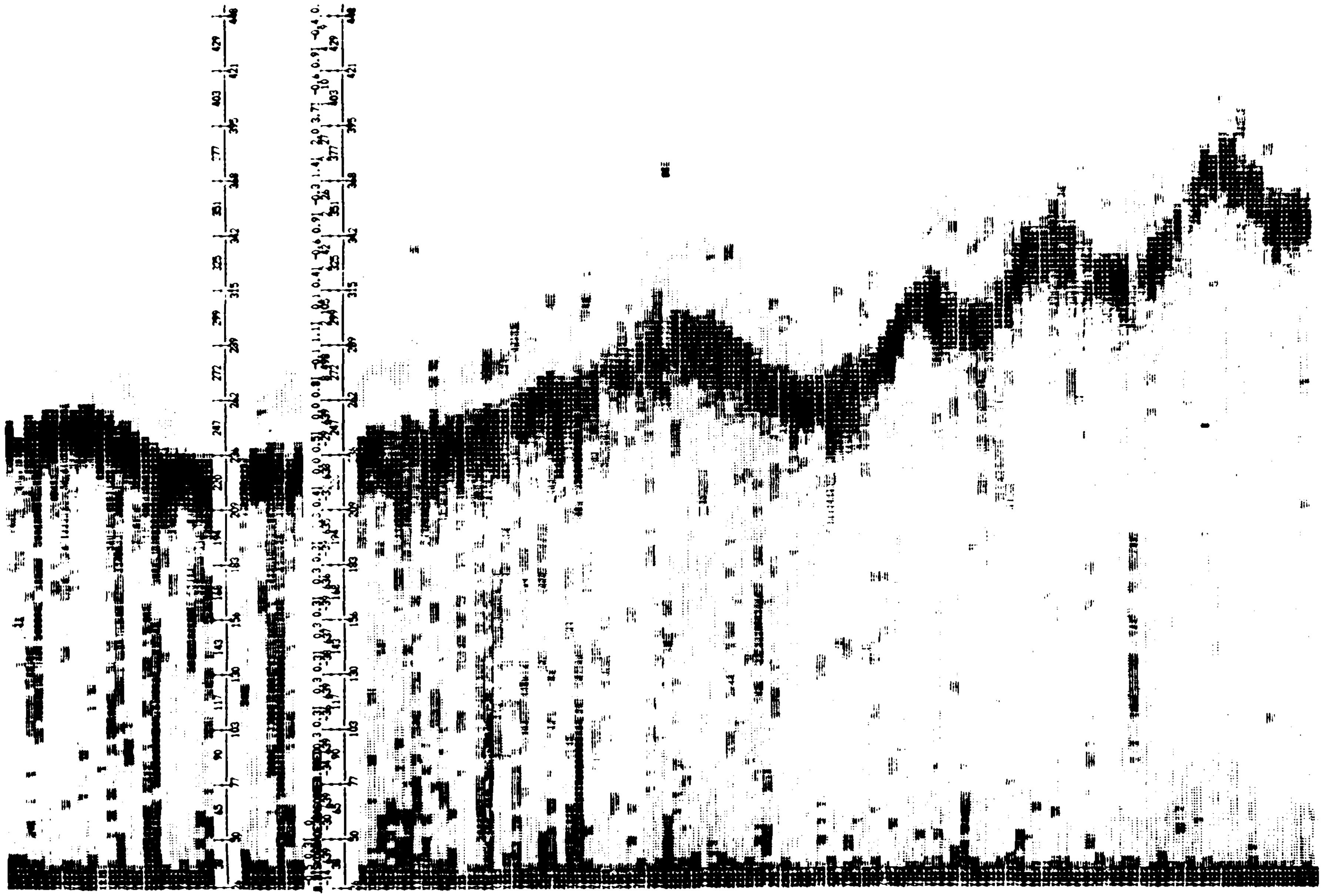


Figure 8. Example of acoustic sounder data provided by Dr. W. Shaw of the Naval Postgraduate School. The output is a time-height section showing the variation in inversion height over a period of approximately 30 minutes. The shading indicates the strength of the return, with the darker shading indicating stronger returns. The column of numbers contains the height scale and wind information. The data was acquired using the sodar shown in Figure 7.

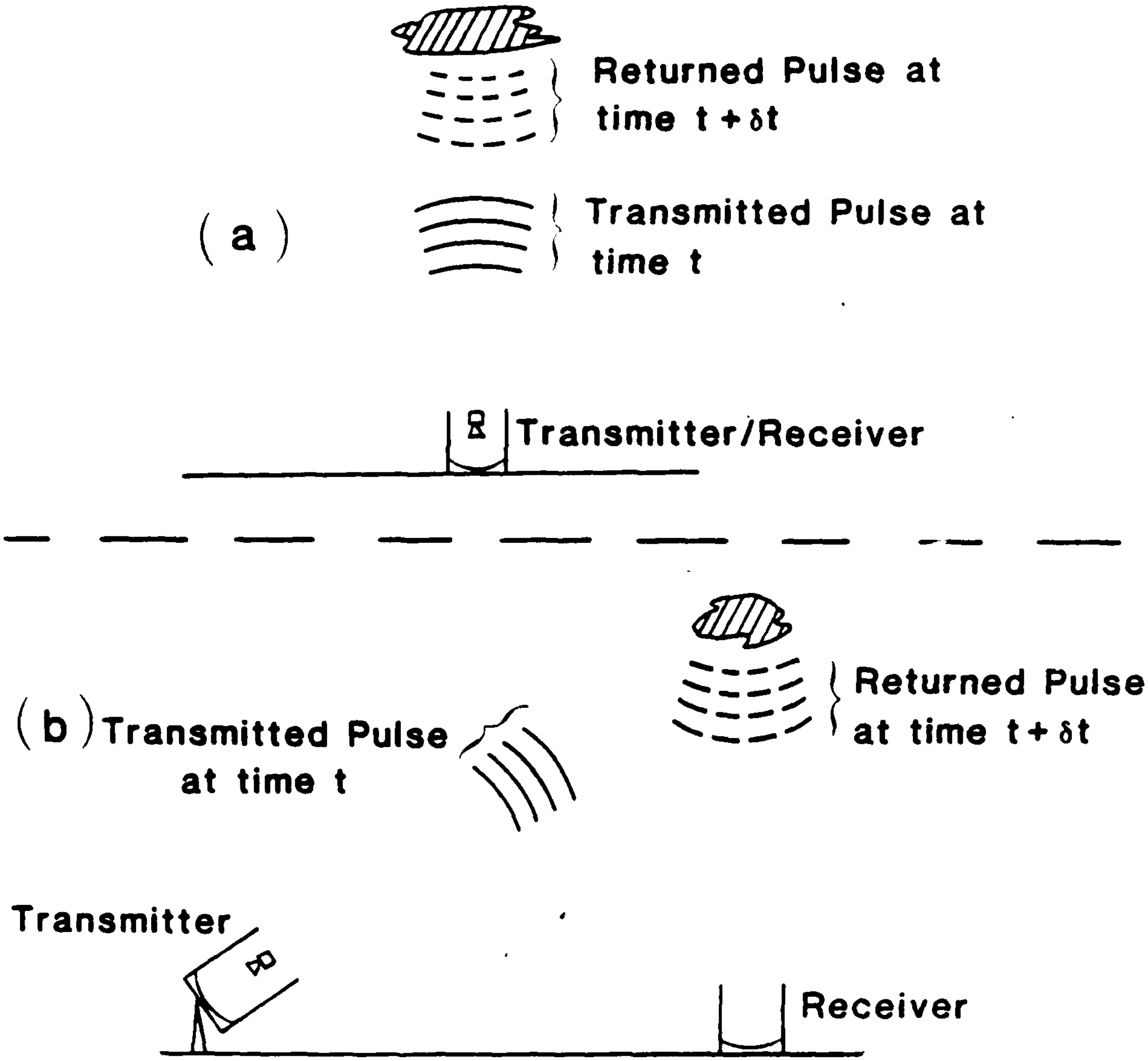


Figure 9. Schematics of the two basic arrangements of antennas in an acoustic sounder. a) A monostatic system uses the same antenna to transmit the pulse and to receive the returned signal. b) A bistatic system uses more than one antenna. Typically one antenna to transmit and one to receive.

The sodar's range is limited to about 1500 meters. Sodars are affected by all types of acoustical noise and shrouds are installed to minimize the effect of ambient noise. One recent installation on a ship did not work due to vibrationally induced noise and other noise sources onboard the ship. The operation is also affected by high winds due to the large horizontal advection of the sound pulse and to noise generated by the wind blowing over the shroud lip. The largest component of a sodar is the antenna system. The antenna itself is between 1.5 and 2 meters in diameter plus the shroud.

The inversion height information obtained with the acoustic sounder could be used as input to the microwave radiometer data reduction and thereby improve the temperature and humidity profiles retrieved. However, since the range of the acoustic sounder is limited approximately to the boundary layer, any improvement in the profiles would be primarily limited to the boundary layer.

2.6 Doppler Acoustic Sounder

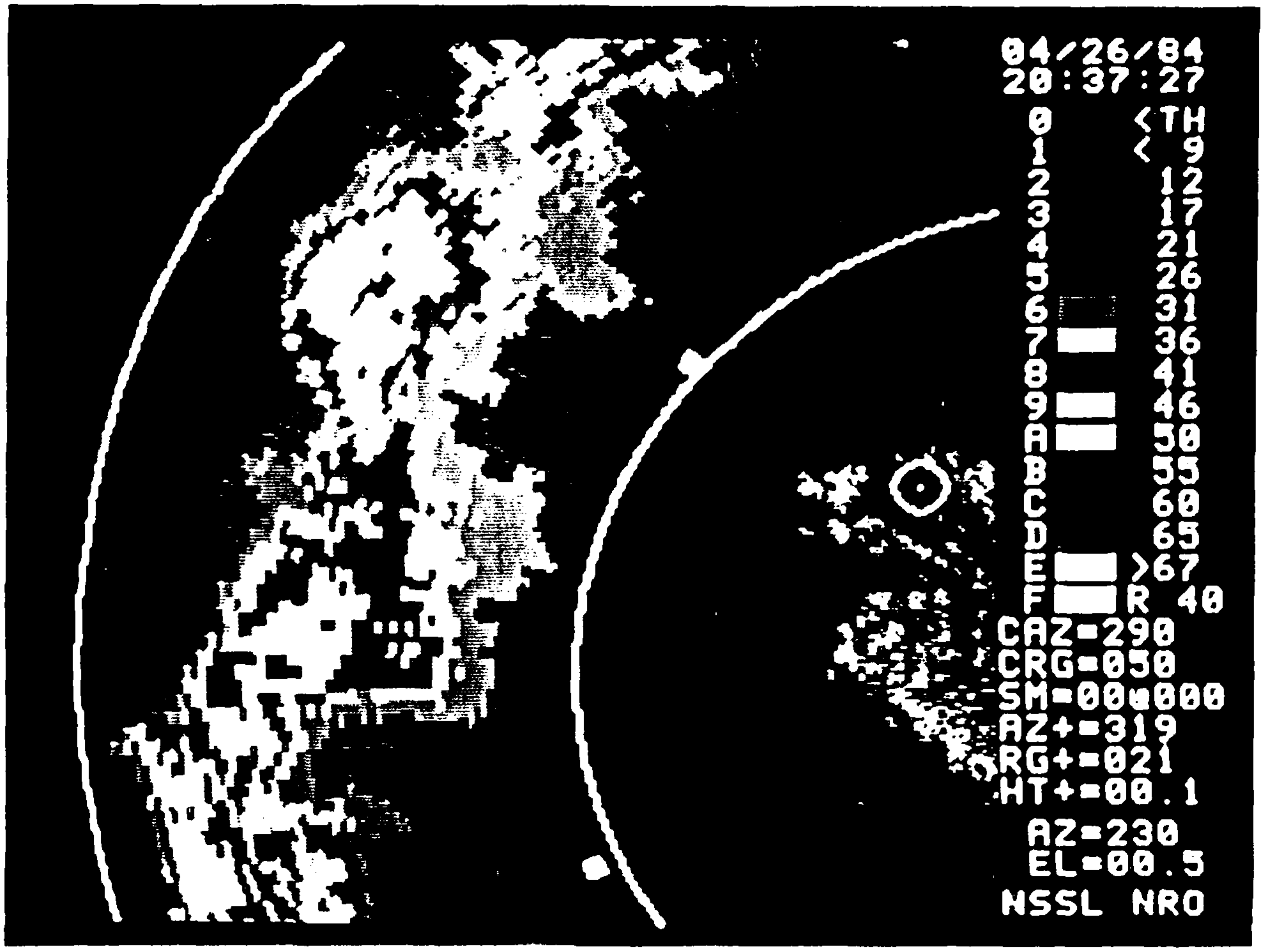
The doppler acoustic sounder is basically the same as the acoustic sounder, but with the added capability of measuring the radial velocities of the targets. By combining three antennas pointing along three axes, the mean wind velocity profile can be extracted. It is subject to the same problems and limitations as non-doppler sodars. The maximum range is approximately 500 meters for velocity measurements. A doppler acoustic sounder was installed on one of the ships during the GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment (GATE) project. However, the returns for the nearly horizontal pointing antennas were contaminated by echoes from the sea surface and had to be discarded. Therefore only vertical velocities were recovered. A doppler acoustic sounder is larger that a non-doppler acoustic sounder because it requires three antennas. The limited extent of the information gained from a doppler acoustic sounder limits its operational Naval afloat applications.

2.7 Conventional Radar

Conventional radar (non-doppler, non-coherent) measures the intensities of returns from meteorological targets. The targets mainly consist of precipitation hydrometeors. The typical resolution is 150 to 600 meters in range and 0.8 to 2.0 degrees in azimuth and elevation. Scan rates are between 2 and 5 rpm. Update rates therefore range from 12 seconds to 10 minutes depending on the scan pattern. Antenna sizes range from 2 to 5 meters depending on the beam width and wavelength.

The returns from precipitation have been extensively studied. With a properly calibrated radar, good estimates of the precipitation intensities can be obtained. Using these estimates, contoured displays of the precipitation can be generated showing the horizontal and vertical structure of the precipitation. Figure 10 is an example of a contoured intensity display showing an intense squall line to the northwest of Norman, OK. The range of precipitation indicated ranges from none to possibly hail and very heavy rain. The Navy's current meteorological radars cannot be calibrated or produce contoured displays because of their design. The lack of calibration and contouring limits the amount of information that can be extracted.

Also obtainable from intensity returns are cloud base heights, cloud top heights, squall line location and movement, and storm intensity estimates. Information can also be extracted from the display by the use of algorithms and computer processing. These include storm intensity, storm motion, automatic echo tracking (Brasunas, 1984), pseudo-internal storm motion (Rinehart, 1979), and liquid water content, which can be used to produce vertically integrated liquid water estimates. Figure 11 is an example of the output from TREC (for Tracking Radar Echoes by Correlation) which is the program developed by Rinehart (1979) to deduce internal storm motions from intensity returns. Bjerkaas and Forsyth (1980) developed an early version of a real time storm analysis package that has been under continual



[illegible]. Example of contoured intensity display. The [illegible] of an intense squall line to the northwest of [illegible], Oklahoma, moving to the southeast. The contouring [illegible] the intensity of the return and thereby the precipitation intensity. Photo courtesy of the [illegible] Laboratory, Norman, OK

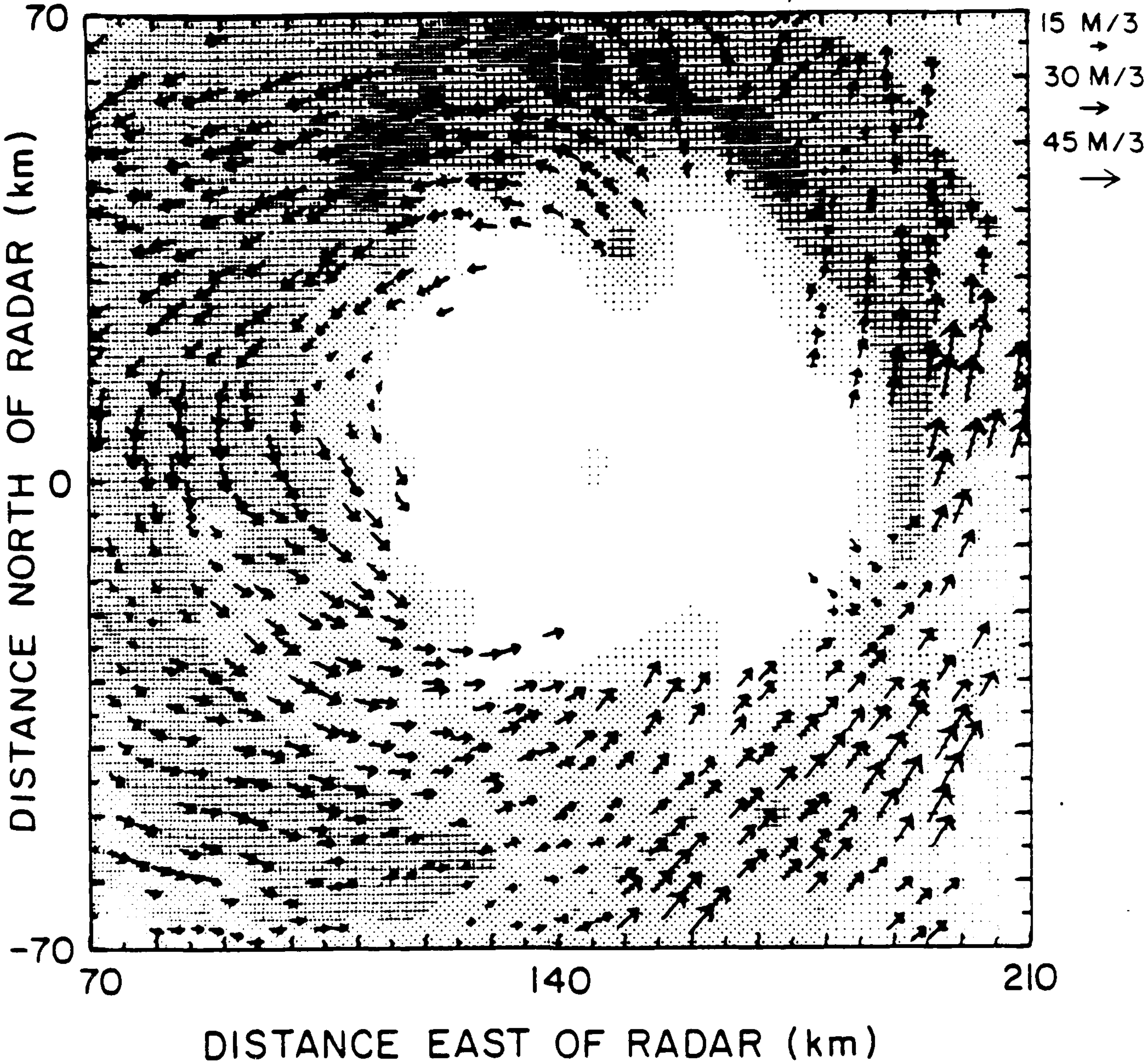


Figure 11. PPI of radar reflectivity data and TREC vectors for Hurricane FREDERIC collected by the Slidell, Louisiana NWS WSR-57 radar at 0331 UT on 12 September 1979 at 0.8 deg elevation. The shaded regions are reflectivity contours starting at 15 dBz and increasing at 10-dB interval (from Rinehart, 1982).

revision and upgrading in conjunction with the Next Generation Weather Radar (NEXRAD) program. It might also be possible to infer regions of increased aircraft icing probability (Smith, 1985). All of the above information can be used to route aircraft or ships or as input to operational decision aids.

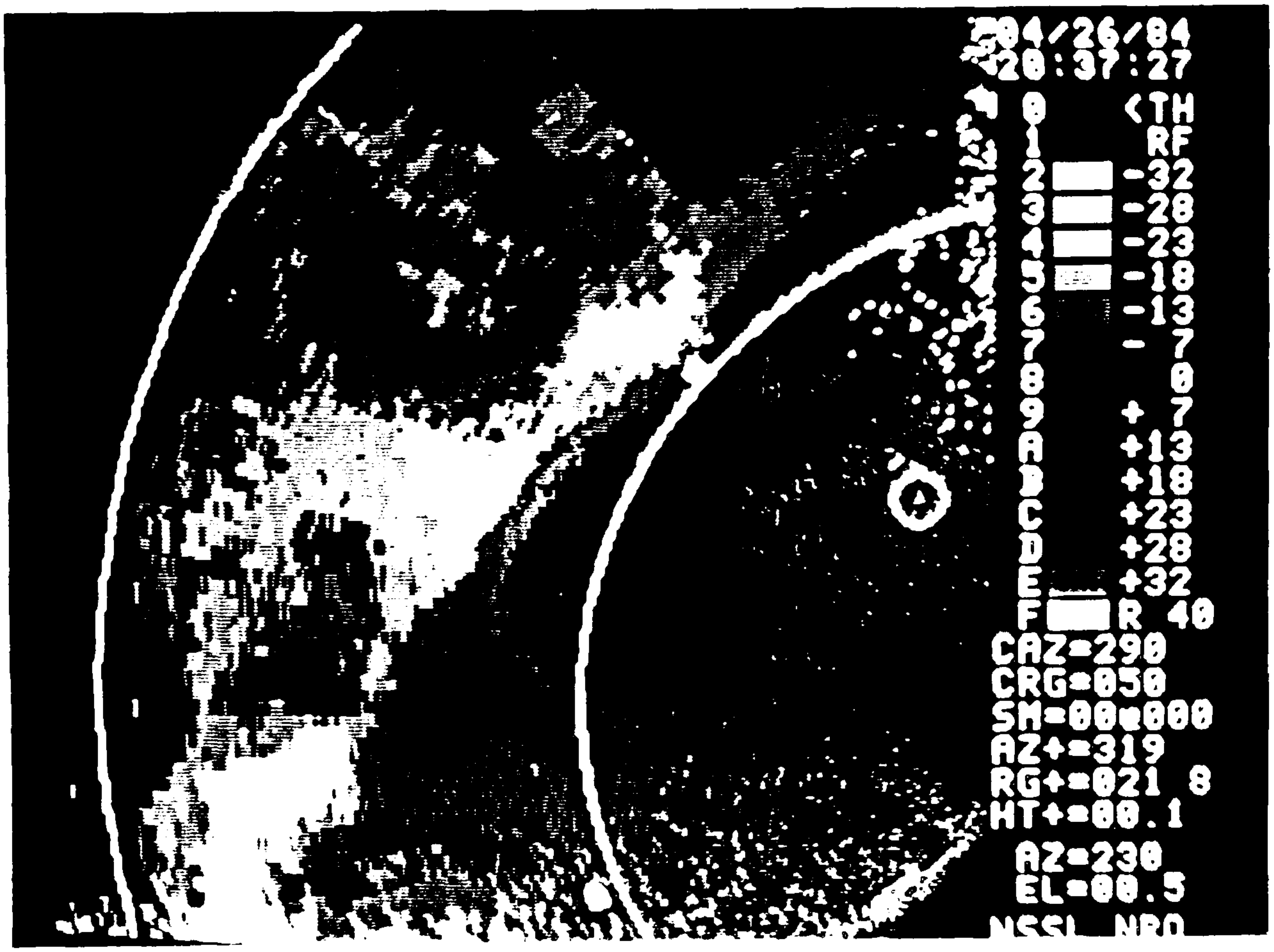
Much of the above will be available to Naval Air Stations in CONUS through Principle User Processors (PUPs) in conjunction with the Navy's participation in NEXRAD.

The major disadvantage of radars is size. The antenna size is directly related to the wavelength and inversely related to beamwidth. For a one degree beamwidth and a 10 cm wavelength the antenna is just over 7m in diameter. Also room is required for the transmitter/receiver and the signal processing equipment. Some of these disadvantages can be overcome by using existing shipboard radars.

2.8 Doppler Radar

In addition to the intensities which are measured by conventional radars, doppler radars also measure the radial velocities of the target and the standard deviation of the velocity estimates (spectral width). Figure 12 is an example of a velocity display showing the winds associated with the squall line shown in Figure 10. Only the radial component of the wind is contoured. A strong convergence line is evident along the leading edge of the squall line. Without the doppler information, the existence of this convergence line could only be guessed. The velocity and spectral width can also be measured in the clear air if sufficient tracers are present. The tracers may be dust, insects, or intrinsic. The intrinsic tracer is turbulence induced refractive index variation on the scale of L/2 and must be in the inertial subrange (see 2.4 UHF/VHF Profilers).

Some of the items that can be determined from the velocity measurements are the mean wind profile, regions of high wind shear, the change in wind direction across fronts, mesocyclones, and the presence, strength, and direction of movement of gust



[illegible] of radial velocity information obtained [illegible] doppler radar corresponding to the [illegible] of Figure 10. Negative velocities are [illegible] and positive velocities are away. A [illegible] can be seen to the northwest with a [illegible] of 60 m/s. Comparison to Figure 10 [illegible] in front of the squall [illegible]. Photo courtesy of the National Severe Storm [illegible]

fronts. Figures 13 to 15 are examples of information available from doppler weather radars. The spectral width helps in identifying regions of high turbulence and wind shear. The velocity and spectral estimates can also be used to help remove ground clutter. Work has been done on extracting two and three dimensional wind fields from the data. Some experimentation is also being done in extracting momentum fluxes, temperature profiles, and refractivity profiles (Gossard et al, 1984). Kropfli (1984), Gal-Chen (1984), and Gal-Chen and Kropfli (1984) discuss the estimation of second order turbulence moments and heat fluxes using single doppler radar.

Due to the navy's participation in NEXRAD, the Naval Air Stations in CONUS will have access to doppler meteorological radar data. Most overseas sites and battle groups, however, do not have access to doppler meteorological information. Within the battle group the doppler meteorological information can be extracted from existing and/or planned tactical radars. What information and how often samples could be obtained would depend on what other operational demands were being placed on the radar system. This could range from full meteorological data acquisition with no other operational demands on the system to no meteorological data acquisition during EMCON.

The range to which reliable meteorological doppler information can be obtained with existing radars will be determined in part by the beamwidth. As the diameter of the sample volume increases, the representativeness of the velocity estimate decreases. Since the diameter of the sample volume increases with range, there is some range beyond which the velocity estimate is no longer reliable. As the beamwidth changes so must this range.

Another problem that needs to be addressed is that of sea clutter, which could contaminate the returns at low elevation angles.

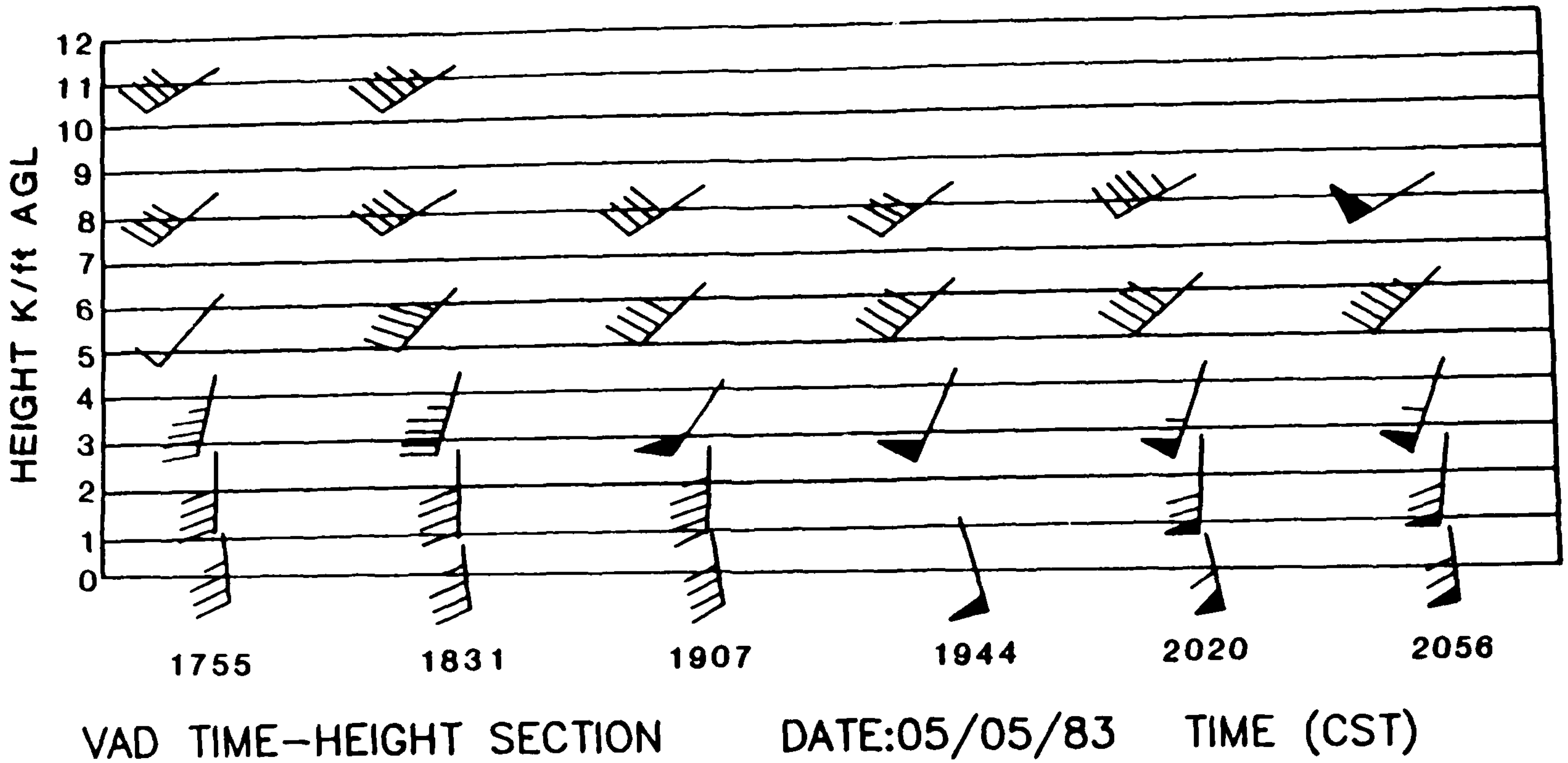


Figure 13. Artist depiction of display of wind profile time history derived from meteorological doppler radar returns. Original display produced by the NEXRAD Initial Operational Test Facility (IOTF) was also color coded.

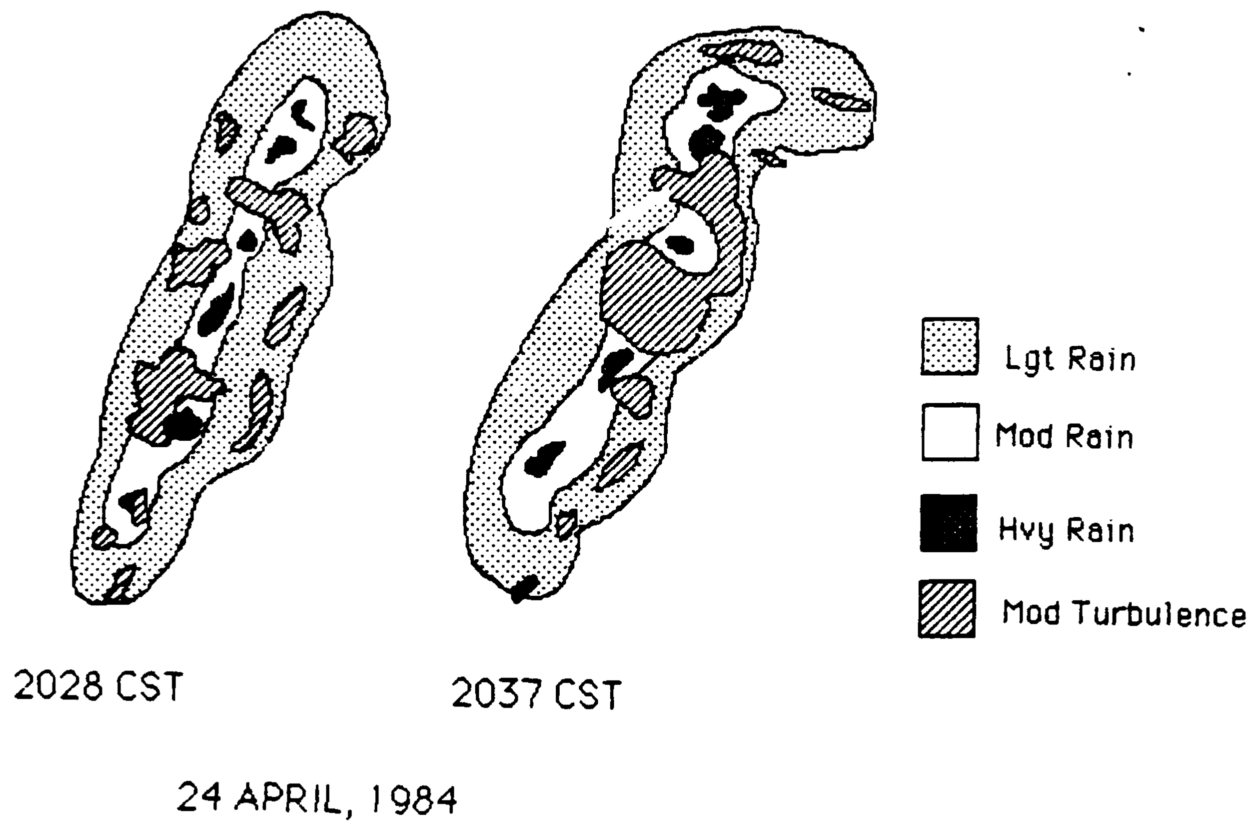


Figure 14. Artist conception of derived output showing simplified contours of precipitation intensity overlayed with regions of moderate turbulence. This type of product could be used to route aircraft. Based on color original produced by the NEXRAD IOTF.

As with nondoppler radars, size could also be a problem. Doppler radars require considerably more signal processing and computational effort than do conventional radars, which would tend to increase the space required.

2.9 Lidar

Lidars are similar to radars except that they use a coherent light source instead of microwaves. Lidars are used to measure cloud base heights, concentrations of atmospheric constituents, temperature, humidity , and aerosol backscatter. The wavelengths used in remote sensing range from the ultraviolet to the infrared. The returns are from dust and aerosols in the atmosphere. Spatial resolution is high, however, and as with radars, there is a near-field problem due to incomplete aperture filling.

There are two main modes of operation: differential absorption and Raman scattering. In differential absorption lidars, also known as DIAL, the difference in the amount of absorption at two or more different transmitted wavelengths is measured and related to the parameter being measured. In a Raman scattering system the laser is used to excite atmospheric constituents, thereby producing Raman radiation. The return signal strengths for two Raman lines corresponding to two different constituents are then compared. Lidars have been built using both methods. DIAL devices tend to be in the infrared while Raman scattering lidars tend to be in the ultraviolet. Ultraviolet wavelengths are used in what are called solar blind lidars. These systems are minimally affected by solar radiation and therefore can be more easily operated during daylight hours.

Lidar systems have been built that measure aerosols (Menzies et al., 1984), water vapor (Hardesty, 1984; Salik, 1983; Cooney, et al., 1985), temperature, inversion heights, cloud base heights, and various other atmospheric constituents (Staehr et al, 1985). Petri et al. (1982) and Salik (1983) discussed the use of a solar-blind Raman lidar to measure water vapor and temperature profiles during day and night hours. They have since measured temperature profiles with a Raman lidar (personal

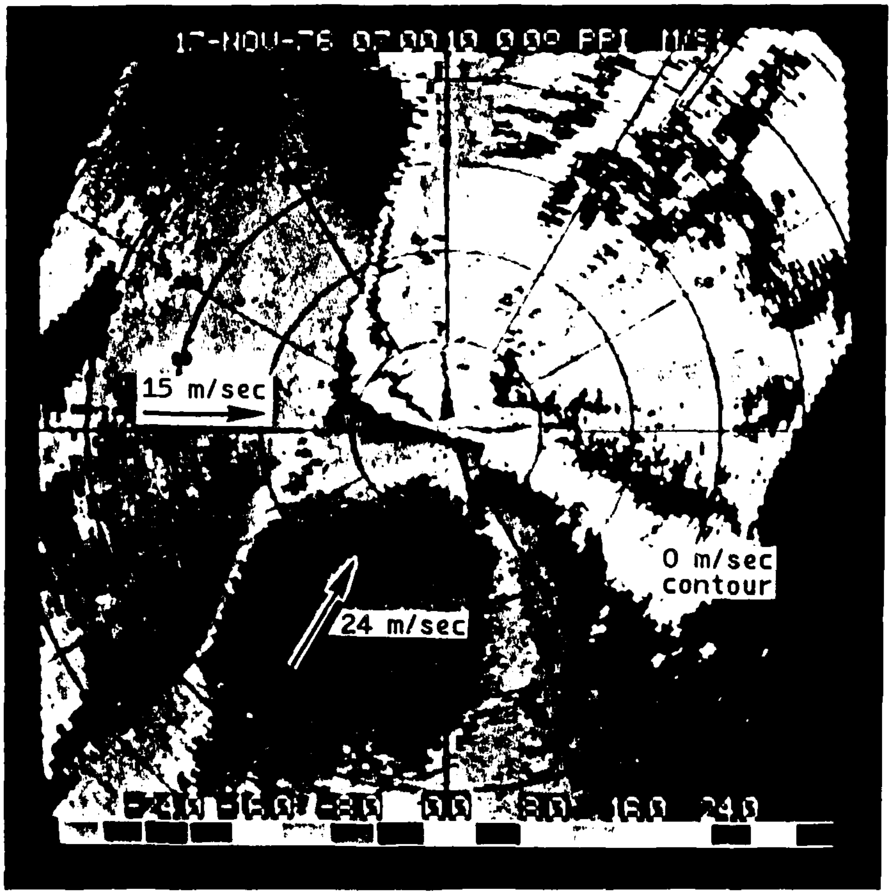


Figure 15. Doppler velocity display of a cold front approaching Ocean Shores, Washington. The display shows a near-surface sharp wind shift line 30 km west of the radar. Note the sharp bend in the zero contour and close packing of the contours. Winds east of the front about 150m above the surface are 200° at 24 m/s and west of the front 280° at 15 m/s. Photo courtesy of Dr. J. Wilson at NCAR.

communication, fall 1985). They also feel that they can accurately determine the inversion levels. Figure 16 is an example of a time-height section of water vapor obtained using a Raman lidar at the Naval Air Development Center (NADC). The figure illustrates the variability of the water vapor profile that can be monitored with a lidar. This variability is also a problem when comparing profiles obtained using lidars with those obtained with a radiosonde, Figure 17. Hooper (1984) describes a lidar used by the Naval Research Laboratory to measure visibility and cloud base heights in field experiments aboard ship. He concluded that the instrument worked well and should be pursued further. Recently, however, the accuracy of extinction coefficient and hence visibility profiles has been questioned by Hughes et al. (1985) and others because of uncertainties in some of the parameters used in the inversion algorithm. New approaches for the measurement of the extinction coefficient are currently being investigated. Experimentation has also been done using a correlation method to estimate the mean horizontal wind. The accuracy of the measurements appears to be good.

The maximum range of lidars is between 2 and 5 km with range resolution varying from meters to hundreds of meters. The near-field problem limits the minimum range to 300 to 500 meters. Beam diameters are between 1 and 10 meters at ranges less than 10 km. The lidars are normally operated in a vertically pointing mode. A lidar with a vertical scanning capability would be able to obtain profiles near the sea surface (Figure 18). It should also be possible to obtain wave spectra by analyzing the return from the sea surface. The wave spectra obtained could be used in ship roll prediction, sea clutter analysis, and other similar applications. The lidar could also be mounted pointing downward on an aircraft and used to obtain profiles in the area of the battle group. The system can require up to several minutes to produce a profile. This is dependent on the transmitted power, the parameter being measured, and the desired accuracy. Lidars have little cloud penetrating ability and are therefore limited when clouds are present.

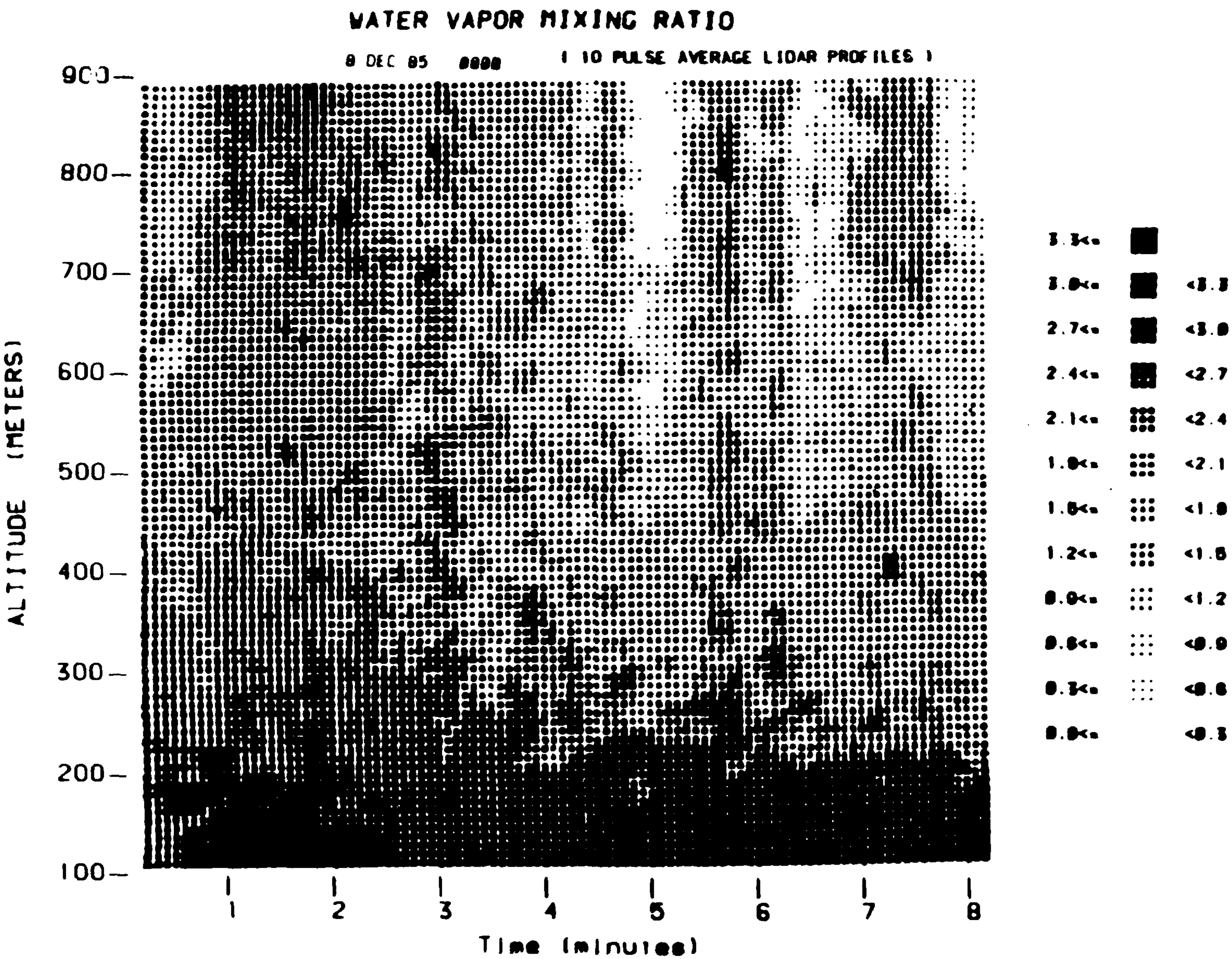


Figure 16. Time height section of water vapor profile obtained using the Naval Air Development Center's (NADC) Raman lidar. The figure shows the high temporal variation of the water vapor profile. Figure courtesy of Al Salik of NADC.

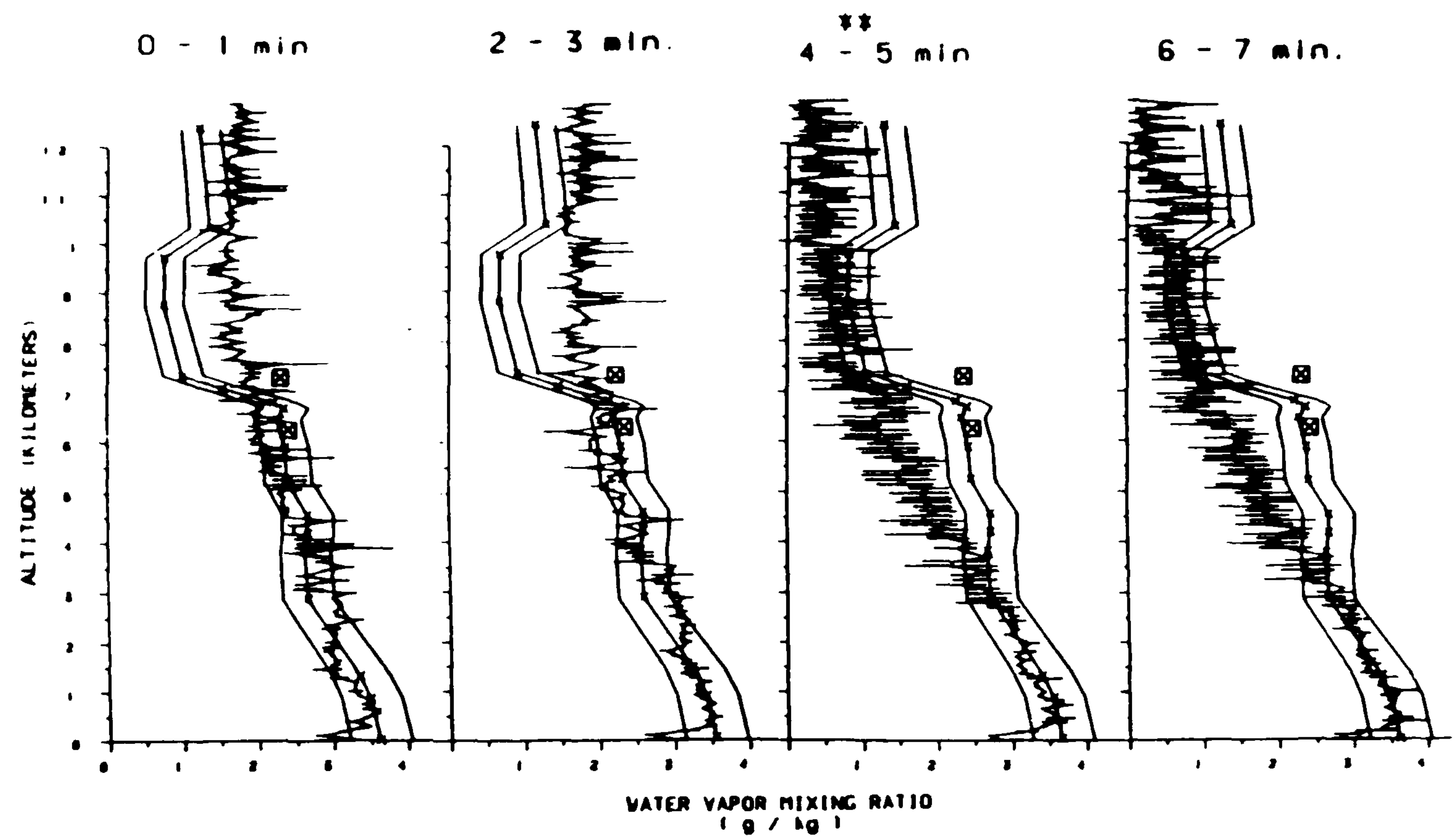


Figure 17. Comparison of vertical water vapor profile obtained with a radiosonde to those obtained with the NADC lidar. The lidar profiles are one minute (120 pulse) averages. The times are the one minute period averaged referenced to radiosonde launch time. The radiosonde error curves were found by assuming combined errors of $\pm 5\%$ relative humidity and $\pm 1°C$ temperature. The horizontal bars indicate the standard deviation of the lidar measurement and is composed of both instrument error and natural variability. Figure courtesy of Al Salik of NADC.

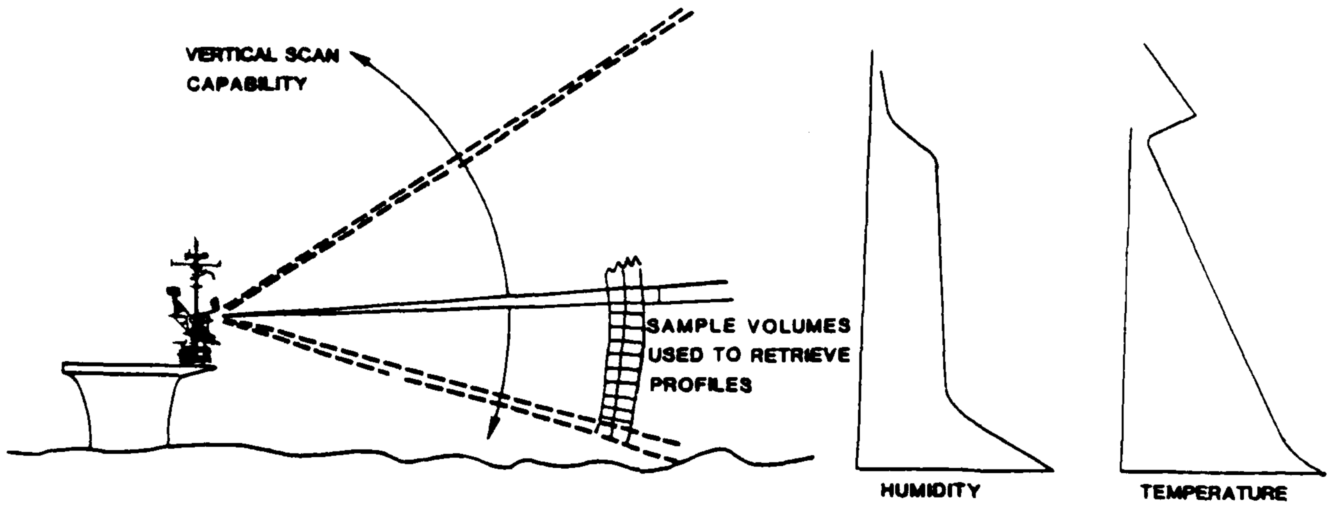


Figure 18. Schematic of how a vertically scanning lidar could be used to obtain profiles of temperature and humidity within the evaporation duct region of the marine boundary layer.

One of the major concerns with lidars is the question of eye safety. Most of the lidars can cause eye damage if improperly used and proper precautions are not taken. How eye safe a lidar can be made, depends on its wavelength, its use, its design, and required power. Eye safety can be improved by well designed operational procedures. Another concern is the maintainability of the optics systems. The alignment of the lenses, mirrors, and filters is critical. Surface deposits can also degrade performance. Size does not appear to be a problem.

2.10 Doppler Lidar

In addition to the parameters measured by nondoppler lidars, doppler lidars can measure radial velocities like doppler radars. Doppler lidars are also known as coherent lidars. Using methods similar to doppler radar, mean wind profiles can be produced. These profiles could be produced during clear air situations when doppler radars may not be able to take measurements. Measurements along at least three axes are required. However, a full 360 degree scan is best (Koscielny et al., 1984; Schwiesow, et al., 1985). The concerns are the same as those for the non-doppler lidar plus the added complexity of the doppler system.

Lidar could be used to obtain wind profiles and/or horizontal wind patterns in clear air. During coastal operations it could be used to map the wind over the coast for helicopter and troop operations (Collis et al., 1966).

The use of a coherent lidar can also extend the range over which atmospheric constituents can be measured. Menzies et al (1984) and Hardesty (1984) have used coherent CO_2 lidars to measure atmospheric aerosol backscatter up to an altitude of 10 km. Figure 19 is an example of backscatter profiles that Menzies (1984) obtained. Figure 20 taken from Hardesty (1984) illustrates how a lidar can monitor rapid changes in atmospheric parameters, in this case backscatter.

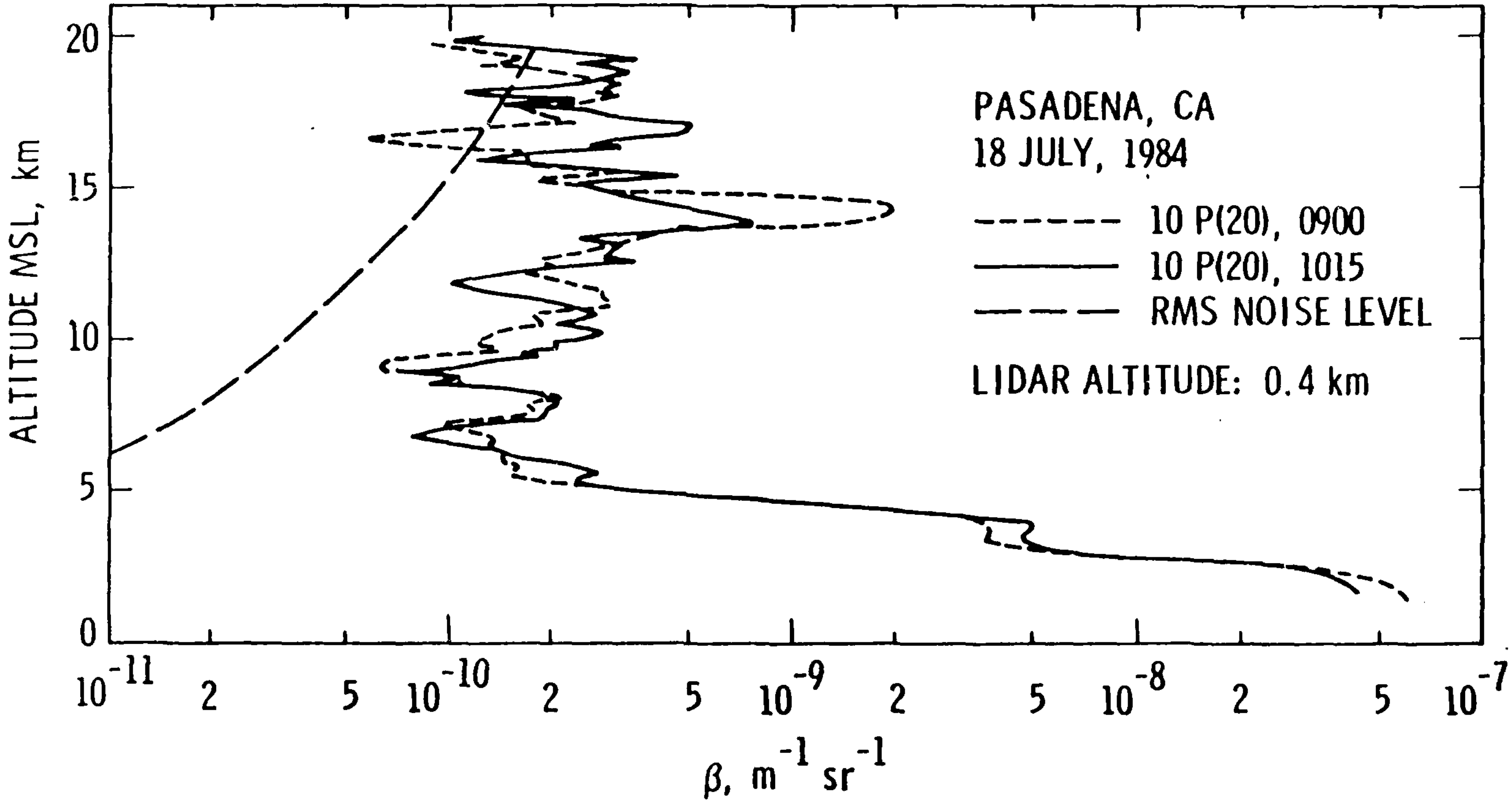


Figure 19. Aerosol backscatter profiles at 9.25 and 10.6 m wavelengths from vertical path data. The peaks and valleys are highly correlated up to 15 km. Above 15 km there is substantial receiver noise influence. Figure courtesy of L. R. Menzies of JPL.

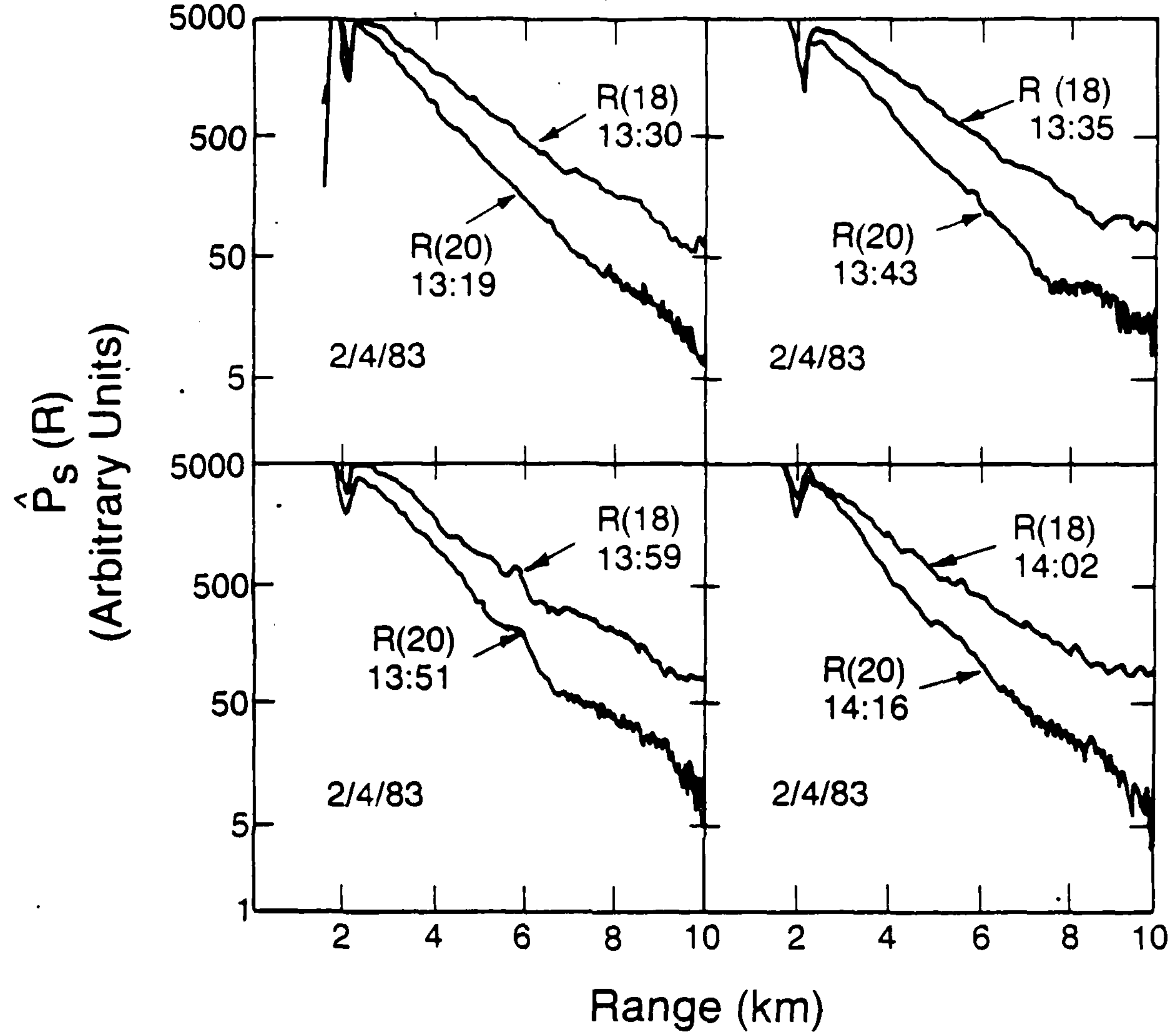


Figure 20. Sequence of measurement profiles showing growth and dissipation of apparent backscatter inhomogeneity at the 6 km range. R(18) indicates the 10.260 m absorbing line and R(20) indicates the 10.247 m line (from Hardesty, 1984).

3. SUMMARY AND RECOMMENDATIONS

3.1 Summary

The variables measured by the instruments reviewed are summarized in Table 2 and the advantages and disadvantages are presented in Table 3. From the tables it is clear that a combination of doppler lidar and doppler radar would provide complete coverage of the required variables in the atmosphere below 6 km under most conditions. The lidar would measure the temperature and humidity profiles required for ducting calculations, and winds in an unobscured atmosphere. An attractive feature of the lidar is that it could be used during EMCON. Radar would provide wind information when precipitation is present in addition to the location, movement, and strength of the precipitation.

Radiosondes would still be required in order to obtain variable profiles above 6 km or when the lidar is inoperative due to obscuration. A microwave radiometer might be used in place of a radiosonde for temperature and humidity profiling if its vertical resolution can be improved sufficiently. The microwave radiometer could also be used during EMCON.

The UHF/VHF profiler is attractive for wind profiling because of its high sampling rate. The space requirements for the antenna system, however, severely limit its application afloat, but there may be ashore applications.

3.2 Recommendations

The following recommendations are made:

1. An examination should be made of the time and space scales of environmental parameters that affect the battle group. The impact of the results on remote sensing requirements as they apply to battle group applications for projects such as TESS (Tactical Environmental Support System) should then be investigated.

2. Research into meteorological applications of radar and lidar should be continued. Models and application algorithms should be developed to demonstrate the usefulness of meteorological lidar and radar data to the battle group.

Table 2. Summary of variables measured by the instruments reviewed. ● = altitude >6 km, ▲ = altitude <6 km, ■ = altitude <2 km. Indicated altitudes are maximums.

INSTRUMENT	WIND	HUMIDITY	TEMPERATURE	INVERSIONS	TURBULENCE	PRECIPITATION INTENSITY	STORM MOTION
RADIOSONDE	●	●	●	●			
MICROWAVE RADIOMETER		▲	●				
UHF/VHF PROFILER	●						
ACOUSTIC SOUNDER	■			■			
NON-DOPPLER RADAR						●	▲
DOPPLER RADAR	●				●	●	▲
NON-DOPPLER LIDAR		▲	▲	▲			
DOPPLER LIDAR	▲	▲	▲	▲	▲		

Table 3. Advantages and disadvantages of the instruments reviewed.

INSTRUMENT	ADVANTAGES	DISADVANTAGES
RADIOSONDE	Experience base	Infrequent samples
	All weather	Expendables
	Measurements to 100 mb	Not usable during EMCON
MICROWAVE RADIOMETER	Passive device therefore usable during EMCON	Low resolution
	High sampling rate	Accuracy decreases with height
UHF/VHF PROFILER	High sampling rate	Antenna size could be a problem
		Precipitation degrades peformance at higher frequencies
		Minimum sampling height approximately 1000 ft
ACOUSTIC SOUNDER (SODAR)	High sampling rate	Sensitive to background noise
	High resolution	Limited range
	Possible use during EMCON	Subject to precip. interference
RADAR	High sampling rate	Not usable during EMCON
	3D coverage of fields	Operational limitations and radar design parameter considerations
		Space and processing requirements
LIDAR	High sampling rate	Maintenance
	High resolution	Eye safety (frequency and operational procedures critical)
	Possible use during EMCON	
	Airborne applications	Not all-weather (operation in fog and precipitation limited)

3. Radar data should be collected at sea using existing afloat radars to determine suitability for meteorological measurement and to assess the potential for clear air return at sea.

4. Application developers should be part of the instrument design team.

5. Tradeoffs of costs, size, and technology should be examined in order to recommend instrument development for the Navy.

6. Developments in microwave radiometers and UHF/VHF profilers should be monitored for improvements that may make their application feasible.

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